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Full Text

Preamble

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Relations between the Fractional Variation of the Ionizing Continuum and C IV Broad Absorption Lines with Different Ionization Levels

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Abstract

This paper explores the correlation between the fractional variation of the ionizing continuum and C IV broad absorption lines (BALs) with different ionization levels. Our results reveal anti-correlations between the fractional variation of the continuum and fractional equivalent width (EW) variation of the C IV BALs without Al III BAL/mini-BALs at corresponding velocities, providing evidence for the widespread influence of ionizing continuum variability on the variation of HiBALs. Conversely, for C IV BALs accompanied by Al III BAL/mini-BALs (LoBAL groups), no significant correlation is detected. The absence of such a correlation does not rule out the possibility that variations in these low-ionization lines are caused by ionizing continuum variability, but rather suggests the influence of BAL saturation to some extent. This saturation effect is reflected in the distribution of the fractional EW variation, where the C IV BAL group accompanied by Al III BAL has a smaller standard deviation for the best-fitting Gaussian component than the two BAL groups without Al III BAL. However, the distribution of fractional variation of their continuum does not show any significant difference. Besides the saturation influence, another potential explanation for the lack of correlations in the LoBAL groups may be the effects of other variability mechanisms besides the ionization change, such as clouds transiting across the line of sight.

Key words: (galaxies:) quasars: absorption lines –(galaxies:) quasars: general –galaxies: active

1. Introduction

Quasar outflows have been proposed as a potential active galactic nucleus (AGN) feedback mechanism that could play a role in terminating star formation in the interstellar medium (ISM) and regulating accretion onto the supermassive black hole (SMBH; Fabian 2012; King & Pounds 2015). In the rest-frame UV spectra of quasars, outflows typically appear as broad absorption lines (BALs) with absorption widths greater than 2000 km s^{-1} (Weymann et al. 1991). "Mini-BALs" are defined as absorption troughs with full widths at half minimum from a few hundred to 2000 km s^{-1} (Hamann & Sabra 2004).

Most BALs exhibit only high-ionization transitions, such as N V, Si IV, and C IV (referred to as HiBALs, as mentioned by Weymann et al. 1991). A smaller fraction, about 15% of BAL quasars, also shows absorption from low-ionization transitions, including Al II, Al III, and Mg II (known as LoBALs, as reported by Voit et al. 1993 and Gibson et al. 2009). Another subgroup, known as FeLoBALs, represents a small subset of LoBALs that exhibit absorption of Fe II or Fe III (Wampler et al. 1995).

BAL variability can serve as a means to assess BAL structures, wind locations, and dynamics, and to constrain the physical mechanisms responsible for AGN outflows. Time variability in individual sources or samples with multi-epoch observations has been reported for HiBALs (e.g., Capellupo et al. 2011, 2012; Filiz Ak et al. 2013; Yi et al. 2019a, 2019b; He et al. 2019), for LoBALs (Zhang et al. 2011; Vivek et al. 2014; McGraw et al. 2017; Sun et al. 2017; Yi et al. 2019a; Yi & Timlin 2021), and for FeLoBALs (Vivek et al. 2012; McGraw et al. 2015; Zhang et al. 2015; Rafiee et al. 2016; Stern et al. 2017). The observed BAL variability can usually be explained by variations in the ionization parameter (e.g., Barlow 1994; Crenshaw et al. 2003; Filiz Ak et al. 2013; Wang et al. 2015; He et al. 2017; Lu & Lin 2018; Lu et al. 2018; Vivek 2019), clouds transiting across the line of sight (e.g., Lundgren et al. 2007; Gibson et al. 2008; Hamann et al. 2008; Krongold et al. 2010; Hall et al. 2011; Filiz Ak et al. 2012; Vivek et al. 2012; Capellupo et al. 2014; Shi et al. 2016; Vivek et al. 2016; Capellupo et al. 2017), or a combination of them (e.g., Capellupo et al. 2012; Vivek et al. 2014). One effective way to determine the variation mechanism of BALs in quasar samples is to investigate the correlation between variability in absorption lines and that of the continuum. Early studies based on relatively small quasar samples reported no detectable correlation between changes in the BAL equivalent width (EW) and the continuum flux (Gibson et al. 2008; Vivek et al. 2014; Wildy et al. 2014). However, recent studies have found anti-correlations between the fractional variation of the continuum and that of both C IV and Si IV BAL troughs in several BAL quasar samples (Lu & Lin 2018; Lu et al. 2018; Vivek 2019). These anti-correlations reveal the widespread influence of ionizing continuum variability on BALs, providing evidence for photoionization-driven BAL variability.

The question of whether these correlations extend to lower and higher ionization levels is still under debate. Vivek et al. (2014) found no clear correlation between absorption line and continuum flux variabilities from a quasar sample of 22 low-ionization quasars that include Mg II and Al III BALs. However, Vivek et al. (2014) pointed out that targets with large absorption line variability also present large variability in their light curves, and they concluded that the observed variability can be well explained by the combination of two mechanisms: continuum variations and clouds transiting across our line of sight.

In typical disk-wind models (e.g., Murray et al. 1995; Proga et al. 2000; Higginbottom et al. 2013), BALs with different ionization levels can be explained by viewing angle effects. More concretely, lower degrees of ionization are observed along lines of sight closer to the accretion disk plane (Hamann & Sabra 2004; Baskin et al. 2013, and Figure 16 [Figure 16: see original paper] of Filiz Ak et al. 2014). This view is supported by observations as well as simulation studies. For example, Filiz Ak et al. (2014) studied the variability characteristics of C IV BAL troughs and whether they also contained accompanying Si IV and/or Al III BAL troughs. Their measurements demonstrate the correlation between changes in ionization level, kinematics, and column density, which is consistent with the predictions of accretion-disk wind models. Low-ionization absorption features in the line of sight typically exhibit deeper and broader C IV BAL troughs, but show smaller minimum velocities and less variation. Recent numerical simulations have also shown that when low-ionization absorption features are present, the BALs are wider and deeper, whereas high-ionization species exhibit higher blue-edge velocities compared to the low-ionization lines (Matthews et al. 2016).

Filiz Ak et al. (2014) have reported correlated changes of BALs with different ionization levels. Building upon their work, this paper aims to explore the correlation between the fractional variation of the ionizing continuum and C IV BALs with different ionization levels. The rest of this paper is organized as follows. Section 2 presents the data preparation and measurements of BALs and spectra. Section 3 contains the results, discussions, and conclusions.

2. Data Preparation and Measurements

The initial sample of this paper containing 671 quasars with at least two-epoch observations was selected by Filiz Ak et al. (2014) from SDSS-I/II/III. The selection criteria for these 671 targets were described in Section 2 of Filiz Ak et al. (2014). In their study, Filiz Ak et al. (2014) identified C IV, Si IV, and Al III BAL/mini-BALs in the spectra of these quasars and classified the C IV BALs into six groups according to whether there are Si IV and/or Al III BALs/mini-BALs at corresponding BAL regions. Specifically, "C IV00" represents C IV BALs without accompanying Si IV and Al III BALs at corresponding velocities during both epochs; "C IVS0" represents C IV BALs with a Si IV BAL at corresponding velocities in one or both epochs, but no corresponding Al III BAL; "C IVSA" represents C IV BALs with both accompanying Si IV and Al III BALs in either epoch; "C IVs0" represents C IV BALs with a Si IV mini-BAL, but no accompanying Al III BAL/mini-BAL is detected; "C IVsa" represents C IV BALs with both accompanying Si IV and Al III mini-BALs; "C IVSa" represents C IV BALs with a Si IV BAL as well as an Al III mini-BAL. In addition, Filiz Ak et al. (2014) defined the corresponding Si IV BALs of C IVS0 as "Si IVS0," the corresponding Si IV and Al III BALs of C IVSA as "Si IVSA" and "Al IIISA," respectively. It is worth noting that among these nine groups, C IV00, C IVs0, C IVS0, and Si IVS0 belong to HiBALs, while C IVsa, C IVSA, C IVSa, Si IVSA, and Al IIISA belong to LoBALs.

We calculated the EW variation (ΔW) of all these detected BAL/mini-BALs, adopting the EW values measured by Filiz et al. (2014) and applied Equation (1) from Lu et al. (2018). We then selected BALs/mini-BALs based on the criterion of $\Delta W > 3\sigma$. The number of BALs included in each of the nine groups from Filiz Ak et al. (2014) and those selected for this article are listed in Table 1 . We then calculated the fractional EW variation (ΔEW/ EW) of our selected C IV, Si IV, and Al III BALs using Equation (2) in Lu et al. (2018).

To obtain the flux density values, we fitted a power-law continuum for each spectrum utilizing the same procedure in Lu et al. (2018). We then used the power-law continuum flux at 1350 Å from the two-epoch spectra of the same quasar to calculate the fractional variation of the ionizing continuum (ΔF_{cont}/ F_{cont}), following Equation (4) in Lu et al. (2018). Figure 1 [Figure 1: see original paper] shows the fractional variation of BALs (ΔEW/ EW) as a function of the fractional variation of the continuum (ΔF_{cont}/ F_{cont}) for nine groups of BALs.

3. Results and Discussions

As shown in Table 1 , anti-correlations between the fractional flux variations of the continuum and fractional EW variations of the BALs in C IV00, C IVs0, C IVS0, and Si IVS0 groups have been confirmed by the Spearman rank correlation analysis (with P-values of Spearman coefficient less than 0.01). It is worth noting that the C IV BALs with lower ionization exhibit smaller correlation coefficients. When the C IV BALs are accompanied by Al III BAL/mini-BALs (C IVsa, C IVSA, C IVSa, Si IVSA, and Al IIISA), no significant correlation is detected. These statistical results are consistent with the expectations of the disk-wind model and provide important insights into the variation mechanism of BALs with different ionization levels.

On one hand, we confirm the anti-correlations between the fractional variations of the continuum and BALs in four groups (C IV00, C IVs0, C IVS0, and Si IVS0) of HiBALs. Previous studies have observed anti-correlations between the fractional variations of the continuum and absorption lines in several BAL samples (Lu & Lin 2018; Lu et al. 2018; Vivek 2019) as evidence for ionization-driven BAL variation. However, these studies did not compare the impact of different ionization states of BALs on the correlation. Our study expands on this by finding anti-correlations between the fractional flux variations of the continuum and fractional EW variations for four BAL groups without Al III BAL/mini-BAL, covering a wider ionization-potential range. This finding provides further evidence of the widespread impact of ionizing continuum variability on the variation of HiBALs (e.g., Weymann et al. 1991). Additionally, in accordance with typical disk-wind models (e.g., Murray et al. 1995; Proga et al. 2000; Higginbottom et al. 2013), if different groups of BALs represent different viewing inclinations, the anti-correlations observed in our study provide evidence for the ubiquitous effects of ionizing continuum variability across a wide range of viewing inclinations.

On the other hand, we found no significant correlations between the fractional flux variations of the continuum and fractional EW variations for the five BAL groups with Al III BAL/mini-BAL (C IVsa, C IVSA, C IVSa, Si IVSA, and Al IIISA), with P-values of Spearman coefficient greater than 0.01. We speculate that the lack of correlations in these groups may be due to the effects of BAL saturation or other variability mechanisms besides ionization changes, such as clouds transiting across the line of sight.

Observations of BAL profiles suffering from saturation have been reported in several previous studies (e.g., Arav 1997; Hamann 1998; Arav et al. 2001; Leighly et al. 2009; Borguet et al. 2012; Xu et al. 2018). For instance, Filiz Ak et al. (2014) have shown that when BAL troughs from lower ionization transitions are present, C IV troughs tend to be stronger and wider (see their Figure 5 [Figure 5: see original paper]) and exhibit more saturation, but less fractional EW variation (see their Figure 11 [Figure 11: see original paper]). This suggests that C IV troughs might experience more saturation when BAL troughs from lower ionization transitions are present. Hamann et al. (2019) also obtained empirical results showing that compared to HiBALs, the C IV BALs in the composite spectrum of LoBALs are deeper and wider (see their Figure 5). Using two sub-samples differing in absorption trough depth, Vivek (2019) found that the shallow trough sub-sample exhibits an even stronger correlation while the deep trough sub-sample shows no correlation between BAL variability and continuum variability (see their Table 3). These results indicate that BAL saturation has a considerable effect on the correlation between BAL variability and continuum variability. The saturation can also be inferred from our Figure 2 [Figure 2: see original paper], which shows that the ΔEW/ EW distribution of the C IVSA group has a smaller standard deviation (σ) for the best-fitting Gaussian component ($\sigma = 0.213$) compared to the C IV00 ($\sigma = 0.390$) and C IVS0 ($\sigma = 0.357$) groups. This is because for saturated troughs, the fractional EW variation measurements can only reflect lower limits of the true variations in optical depth and column density, thus weakening the correlation between absorption line variability and continuum variability. However, the ΔF_{cont}/ F_{cont} distribution of C IVSA does not show any significant difference compared to the C IV00 and C IVS0 groups (according to the K-S test results, with $P > 0.026$). Considering the significant impact of line saturation in the C IVSA group, we speculate that the effects of ionizing continuum variability may also exist in BALs that accompany Al III BAL/mini-BALs. In other words, the ubiquitous effects of ionizing continuum variability may extend to even lower viewing inclinations.

Another potential explanation for the lack of correlations in our LoBAL groups could be the transiting of clouds across our line of sight. The transiting scenario has been reported to be a feasible cause of absorption-line variability (e.g., Hamann et al. 2008; Capellupo et al. 2017). For example, if a highly saturated C

IV BAL exhibits clear variability, it provides evidence in favor of the transiting scenario. This is because a highly saturated C IV BAL is not easily affected by small changes in ionization but can easily exhibit variations due to the transiting of outflows (e.g., McGraw et al. 2018). The presence of a P V BAL can serve as a detector for highly saturated C IV BALs at corresponding velocities (e.g., Capellupo et al. 2014, 2017; McGraw et al. 2018). To place further constraints on the origin of variability in our LoBAL subsamples, it is necessary to check individual spectra, which is beyond the scope of this paper.

In summary, we have discovered anti-correlations between the fractional variation of the continuum and fractional EW variation of C IV BALs in four HiBAL groups, while no significant correlation was found in five LoBAL groups. The anti-correlations presented in four HiBAL groups demonstrate the widespread impact of ionizing continuum variability on the variation of outflow absorption. The lack of correlations in five LoBAL groups does not rule out the possibility that variations in these low-ionization lines are caused by ionizing continuum variability, but rather suggests the influence of BAL saturation to some extent. We have tested the ΔEW/ EW and ΔF_{cont}/ F_{cont} distributions of the C IV00, C IVS0, and C IVSA groups (Figure 2 [Figure 2: see original paper]) to reveal the saturation influence. Another potential explanation for the lack of correlations in the LoBAL groups may be the effects of other variability mechanisms besides ionization changes, such as clouds transiting across the line of sight.

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